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ISOTOPE HEAT SOURCE SIMULATOR FOR TESTING OF SPACE POWER SYSTEMS

by George M. Prok and Robert B. Smith

Lewis Research Center
Cleveland, Ohio 44135

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • DECEMBER 1973

1. Report No. NASA TM X-2962	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle ISOTOPE HEAT SOURCE SIMULATOR FOR TESTING OF SPACE POWER SYSTEMS		5. Report Date December 1973
		6. Performing Organization Code
7. Author(s) George M. Prok and Robert B. Smith		8. Performing Organization Report No. E-7616
9. Performing Organization Name and Address Lewis Research Center National Aeronautics and Space Administration Cleveland, Ohio 44135		10. Work Unit No. 502-25
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		13. Type of Report and Period Covered Technical Memorandum
		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

A reliable isotope heat source simulator has been designed for use in a Brayton power system. This simulator is composed of an electrically heated tungsten wire which is wound around a boron nitride core and enclosed in a graphite jacket. Simulator testing was performed at the expected operating temperature of the Brayton power system. Endurance testing for 5012 hours was followed by cycling the simulator temperature. The integrity of this simulator was maintained throughout testing. Alumina beads served as a diffusion barrier to prevent interaction between the tungsten heater and boron nitride core. The simulator was designed to maintain a surface temperature of 1311 to 1366 K (1900° to 2000° F) with a power input of approximately 400 watts. The design concept and the materials used in the simulator make possible many different geometries. This flexibility increases its potential use.

17. Key Words (Suggested by Author(s)) Isotope heat source; Diffusion barrier; Space power; Brayton engine; Material compatibility		18. Distribution Statement Unclassified - unlimited	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 14	22. Price* Domestic, $2.75 Foreign, $5.25

* For sale by the National Technical Information Service, Springfield, Virginia 22151

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SUMMARY

A reliable isotope heat source simulator has been designed for use in a Brayton power system. This simulator is composed of an electrically heated tungsten wire which is wound around a boron nitride core and enclosed in a graphite jacket. Simulator testing was performed at the expected operating temperature of the Brayton power system. This temperature of 1330 K (1935° F) was maintained for 5012 consecutive hours. Temperature cycles that might occur during a Brayton engine test were simulated after the endurance testing. The simulator maintained its integrity throughout the cycling tests. The electrical power required to maintain a 1330 K (1935° F) surface temperature was 430 watts, which is only slightly higher than the nominal value of 400 watts from the actual isotope heat source.

The alumina beads around the tungsten heating element were an excellent diffusion barrier. They did not react with either the tungsten or the boron nitride core. However, there was some vacuum evaporation of the alumina. A posttest inspection indicated that the isotope heat source simulator should last well in excess of the 5012 hours of testing.

The design concept and the properties of the materials in the heat source simulator make possible geometries other than the one tested. This flexibility increases its potential use.

INTRODUCTION

Lewis Research Center has developed and tested a Brayton cycle power-conversion system for space application (refs. 1 to 4). The development work was done by heating the working gas with an electric heat source. In a flight version, energy from a nuclear heat source will be used to heat the working gas. For the 2- to 10-kilowatt Brayton cycle power system, an array of isotope heat sources, as shown in figure 1, would be required (refs. 5 and 6). The isotope fuel of a heat source is encased in a metal con-

tainer; a graphite jacket around the metal container is required for reentry protection (ref. 5).

Because of radiation and possible contamination of the surroundings, isotope fuels are inherently hazardous and difficult to handle. The large quantities and high temperatures of the isotope fuel required for operation of a Brayton engine increases the hazard. Therefore, for checkout and preliminary testing of a Brayton engine, it is desirable to use an electrically simulated isotope heat source. In a previous test, an isotope heat source simulator has been operated for nearly 600 hours at rated power (400 W) and temperature (1311 K, 1900° F) at the Space Power Facility of NASA's Plum Brook Station (ref. 6). A planned shutdown was made after the 600 hours of testing. Inspection of the heat source simulator showed material compatibility problems. There was an interaction between the tungsten filament and the boron nitride core. This interaction was to such a degree that it would be impossible to predict the potential life of other heat source simulators which are made similar to that reported in reference 6. Material compatibility in the temperature range required of an electrically simulated isotope heat source for the testing of a Brayton engine is an area of technology where little is known.

This report describes an isotope heat source simulator that has overcome the material compatibility problems. Also included are the results from endurance testing and heat source cycling. Throughout this report the isotope heat source simulator may be referred to as a heat source simulator or simply simulator.

DESIGN OF SIMULATED ISOTOPE HEAT SOURCE

The isotope heat source simulators must be suitable for integration with the isotope Brayton engine discussed in reference 4 and shown schematically in figure 2. For flight safety reasons, the isotope heat source array must be mounted in a reentry vehicle (ref. 5). Also, each individual heat source must be capable of reentering alone; this requires a protective outer jacket of fine-grained graphite. The outer surface of the electrically powered heat source simulator must be made of the graphite reentry material to provide the same thermal properties as the isotope heat source. Other characteristics include the following:

(1) Testing power range of 400 to 500 watts

(2) Graphite surface temperature of about 1360 K (1990° F) at a heat source power output of approximately 400 watts

(3) Capability of operating at temperature and power for 5000 hours

(4) Capability of operating at 10 percent over power

(5) Capability of cycling the heat source power and temperature without heat source failure

(6) Capability of arranging the heat source simulator in the array shown in figure 1

The heat source simulator tested in reference 6 is shown in figure 3. In this design, the tungsten wire is in contact with the boron nitride core, and both ends of the tungsten wire exit at the same end of the heat source simulator. Design changes that were made in order to meet the test objectives are shown in figure 4. These changes include the following:

(1) Alumina beads around the tungsten wire to act as a diffusion barrier against the tungsten/boron nitride interaction

(2) Electrical connections for the tungsten wire heating element at each end of the heat source simulator in order to easily assemble the array shown in figure 1

One end of both the graphite outer jacket and the boron nitride core were keyed to prevent the core from turning in the jacket (fig. 4(b)). The tungsten wire had a 0.51-millimeter (20-mil) diameter and was 213 centimeters (81 in.) long in order to meet test requirements (refs. 5 and 7).

APPARATUS AND PROCEDURE

Test objectives require the heat source simulator to be tested in an insulated container at pressures less than 1.3×10^{-2} newton per square meter (1×10^{-4} torr). The insulated container and some of the instrumentation are shown in figure 5. Additional test instrumentation is shown in the test setup schematic (fig. 6). The insulated container consisted of alternate layers of microquartz felt insulation and sheet metal except for the top (fig. 5). Niobium-zirconium alloy sheet was nearest the heat source simulator. Stainless steel sheet was on the outer two layers. As shown in figure 5, the top of the container was primarily microquartz felt. The inner can of niobium-zirconium alloy was in contact with microquartz at the top and alumina beads on the bottom. The alumina beads separated the inner can from contact with a niobium-zirconium table. There was a void space between the sides of the can and the first inside sheet of niobium-zirconium. The isotope heat source simulator rested on the apex of three boron nitrate prisms inside the refractory metal can. The size of the entire package is 33 centimeters in diameter by 40.6 centimeters high. Power leads, thermocouple leads, and a pressure tap penetrate the insulation as shown in figure 5. The total insulation package was sufficient to give the proper in vacuum operating condition for the heat source simulator. These conditions are a 1360 K (1990° F) surface temperature at outputs of 400 to 500 watts. A belljar vacuum system was used in the test setup.

The instrumentation includes the following:

(1) Three platinum/platinum - 13-percent-rhodium thermocouples on the surface (attached with high temperature cement)

(2) A thermocouple on the outside of the insulation container

(3) An ionization gage to measure the pressure inside the insulation container

(4) Belljar vacuum gages (thermocouple and ionization gages)

(5) An ammeter and voltmeter for determining the power to the heat source

After the isotope heat source simulator was installed and prepared for testing, pumpdown was initiated. It took 284 hours to pump the belljar down to 5×10^{-4} newton per square meter (4×10^{-6} torr). Pumpdown was followed by a bakeout period of 120 hours (fig. 7). During the first 29 hours of the bakeout period, 20 to 40 watts were applied to the heat source simulator. This was done to increase the outgassing rate of the insulation. Seventeen days after the initiation of pumpdown the pressure inside the insulation was 6.5×10^{-4} newton per square meter (5×10^{-6} torr), and the belljar pressure was 2×10^{-4} newton per square meter (1.5×10^{-6} torr). At this point, the power to the heat source simulator was gradually increased. The rate of power increase was governed by the pressure inside the insulation. This pressure was always kept in the 10^{-2} newton per square meter (10^{-4} torr) range or below. Higher pressures could cause premature failure of the tungsten wire heating element.

Because of the large amount of outgassing from the insulation, it took 16 days to reach the steady-state test conditions. These conditions were as follows:

(1) Heat source simulator voltage, 57 volts

(2) Heat source simulator current, 8.8 amperes

(3) Heat source simulator surface temperature at TC-1 (fig. 5), 1330 K (1935° F)

(4) Maximum pressure inside insulation container, 6×10^{-3} newton per square meter (5×10^{-5} torr)

(5) Maximum pressure in belljar, 7×10^{-4} newton per square meter (5.5×10^{-6} torr)

The pressures inside the insulation and belljar decreased during the test to 2.7×10^{-4} and 1.5×10^{-4} newton per square meter (2×10^{-6} and 1.1×10^{-6} torr), respectively.

After the endurance part of the test was complete, the heat source simulator power and surface temperature were cycled. This was done by permitting the heat source simulator to cool to various temperatures and then reheating it to a surface temperature of at least 1310 K (1900° F).

Following the completion of testing, the heat source simulator was allowed to cool before being disassembled. The various components of the heat source simulator were examined for material compatibility. Material analysis was by X-ray diffraction using CuK alpha radiation with a nickel filter.

RESULTS AND DISCUSSION

Endurance testing of the isotope heat source simulator was stopped after successful operation for more than 5000 continuous hours (fig. 7). During the endurance test, the nominal heat source simulator power was 430 watts. This power was corrected for 1 lead losses. The time-temperature plot in figure 7 is for TC-1 (fig. 5). The temperatures at TC-2 and TC-3 were both 1313 K (1905° F). These temperatures compare favorably with the 1330 K (1935° F) at TC-1. The small difference in temperatures between TC-1, TC-2, and TC-3 is what one expects and desires from a real isotope heat source (ref. 5).

During checkout and preliminary testing of an isotope Brayton engine, some temperature cycling of the heat source simulator might be expected. The capability of the heat source simulator to withstand temperature cycling was determined after endurance testing. The cycling from five different temperatures to more than 1310 K (1900° F) is shown in figure 7. There was no failure in the heat source simulator after completion of the cycling test. The fact that the cycling was performed after the endurance testing gives more confidence in the ability of the heat source simulator to withstand temperature cycles.

The heat source simulator was visually inspected after completion of the tests. From this inspection, the heat source simulator appeared to be capable of withstanding much further operation. Although a few of the alumina beads were cracked, the tungsten heating element appeared to be completely unaffected. The inside of the graphite jacket had a grayish deposit. The boron nitride core that was adjacent to the alumina beads had a white colored deposit. Also streaks of gray appeared on the boron nitride opposite the joints of the alumina beads.

Samples from various locations of the heat source simulator were analyzed by X-ray diffraction. Results of the analysis are shown in table I. The results show that the primary compounds detected in the various deposits are aluminum oxide (Al_2O_3) and magnesium orthosilicate (Mg_2SiO_4). The Mg_2SiO_4 comes from the high temperature cement used for attaching the thermocouple. This high temperature cement was only used for test purposes to provide heat conduction path from graphite to thermocouples and to prevent interaction between graphite and platinum in the thermocouples; it is not an integral part of the isotope heat source simulator. The source of the Al_2O_3 is from the alumina beads around the tungsten heating element (fig. 4(a)). All other compounds detected were either insignificant or would not jeopardize the integrity of the heat source simulator.

Since the alumina beads serve as a diffusion barrier between the tungsten and boron nitride, they were examined more closely. Seven beads near the center of the boron nitride core and seven beads near the electrical connection were weighed and photo-

graphed. The beads near the electrical connections were not in contact with the boron nitride. The results from the weighing showed that the beads near the center of the core averaged 39 percent lighter than those near the electrical connections (table II). Enlarged photographs of the bead ends show that the weight loss of the beads near the core center is from the side facing the boron nitride. The reason for this is that the bead radiates heat to the core which in turn radiates the heat back to the bead. The outside of the bead is radiating to the graphite which adsorbs and does not radiate as much heat back to the beads as the boron nitride core does. This results in a higher temperature on the surface of the Al_2O_3 bead next to the boron nitride core, which in turn accounts for the higher losses by vacuum evaporation from that side of the bead.

CONCLUDING REMARKS

The isotope heat source simulator designed to overcome earlier material compatibility deficiencies successfully met test objectives. The endurance test of 5012 hours at 1330 K (1935° F) was followed by cycling the heat source simulator power and surface temperature. The cycling was from various initial temperatures up to 1310 K (1900° F). The lowest temperature in the cycling was near room temperature.

Inspection and material analysis after the test showed the following:

1. Alumina beads acted as an excellent diffusion barrier between the tungsten heater and the boron nitride core.

2. Alumina beads adjacent to the boron nitride did vacuum evaporate to a small degree.

3. The tungsten heater should last extremely long under the test conditions of the isotope Brayton engine.

The heat source simulator that was tested had a hexagonal cross section which electrical leads at each end. This was the geometry tested because of the isotope Brayton heat source array which was required to meet flight specifications. However, the physical properties of the materials in the heat source simulator and the material compatibility make other geometries possible. The flexibility in the design of this heat source simulator increases its potential use - for example, a simulator for testing thermoelectric generators.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 3, 1973,
502-25.

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TABLE I. - SUMMARY OF X-RAY DIFFRACTION DATA

Sample	Compounds detected	Remarks
Deposit on inside diameter of graphite shell	Al_2O_3 (aluminum oxide) Mg_2SiO_4 (magnesium orthosilicate)	Constituent of high temperature cement
Insulator beads	Al_2O_3	
Greyish powder inside lid	BN Graphite	In direct contact with BN core
High temperature cement	Mg_2SiO_4 (magnesium orthosilicate)	No carbon, BN, or Al_2O_3 detected
Deposit on BN core	Al_2O_3 (aluminum oxide) W (tungsten, small amount)	Al_2O_3 is vaporizing from insulator beads and condensing on BN; weak tungsten lines indicate little is evaporating

TABLE II. - WEIGHTS OF Al_2O_3 BEADS

Al_2O_3 beads not in contact with BN core, g	Al_2O_3 beads in contact with BN core, g
0.0116	0.0083
.0109	.0044
.0105	.0062
.0106	.0072
.0108	.0078
.0110	.0048
.0100	.0072
Average: 0.0108	Average: 0.0066

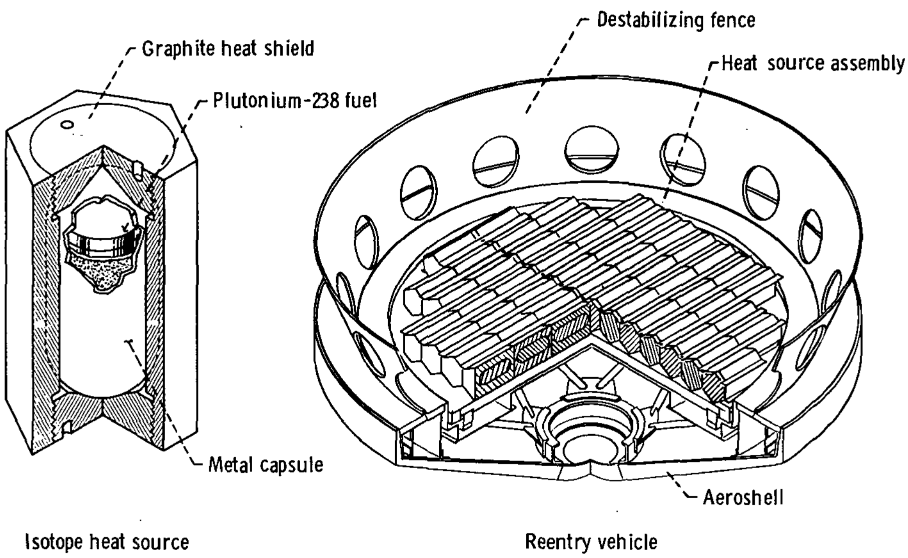


Figure 1. - Brayton isotope heat source unit.

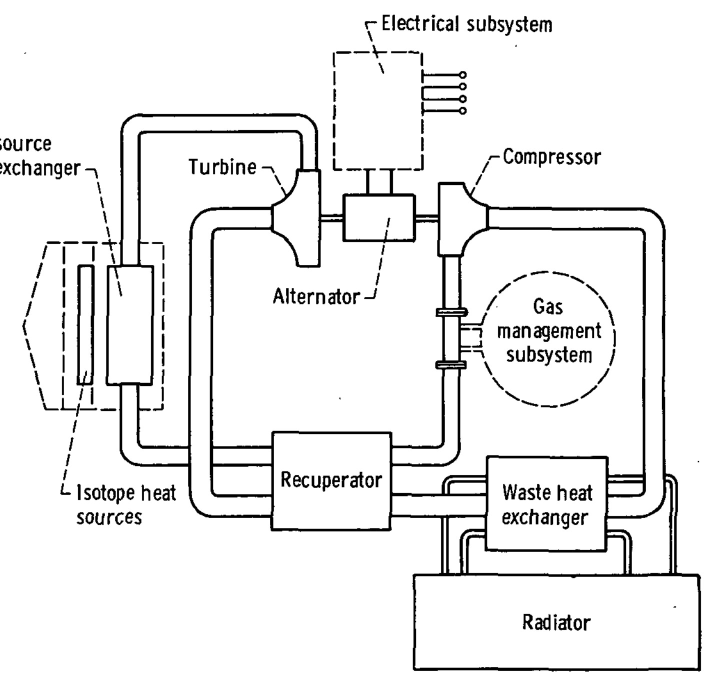


Figure 2. - Schematic diagram of Brayton power system.

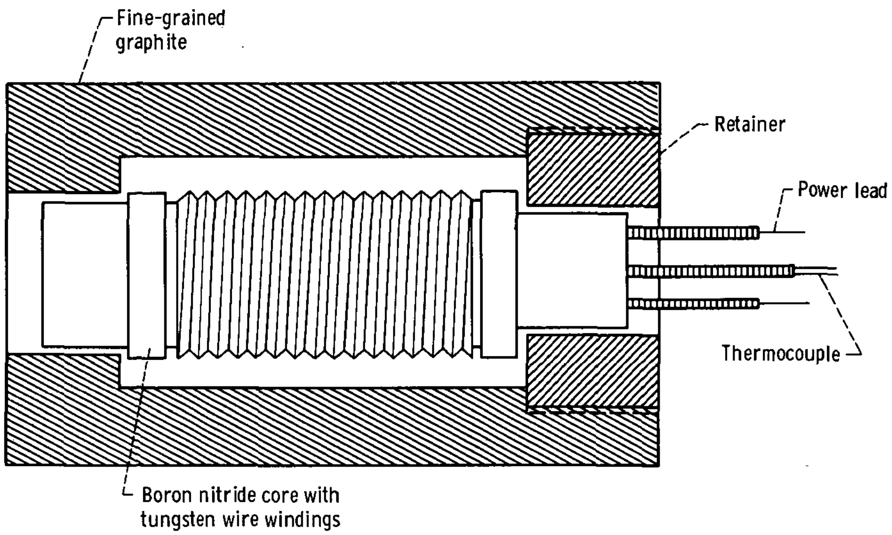
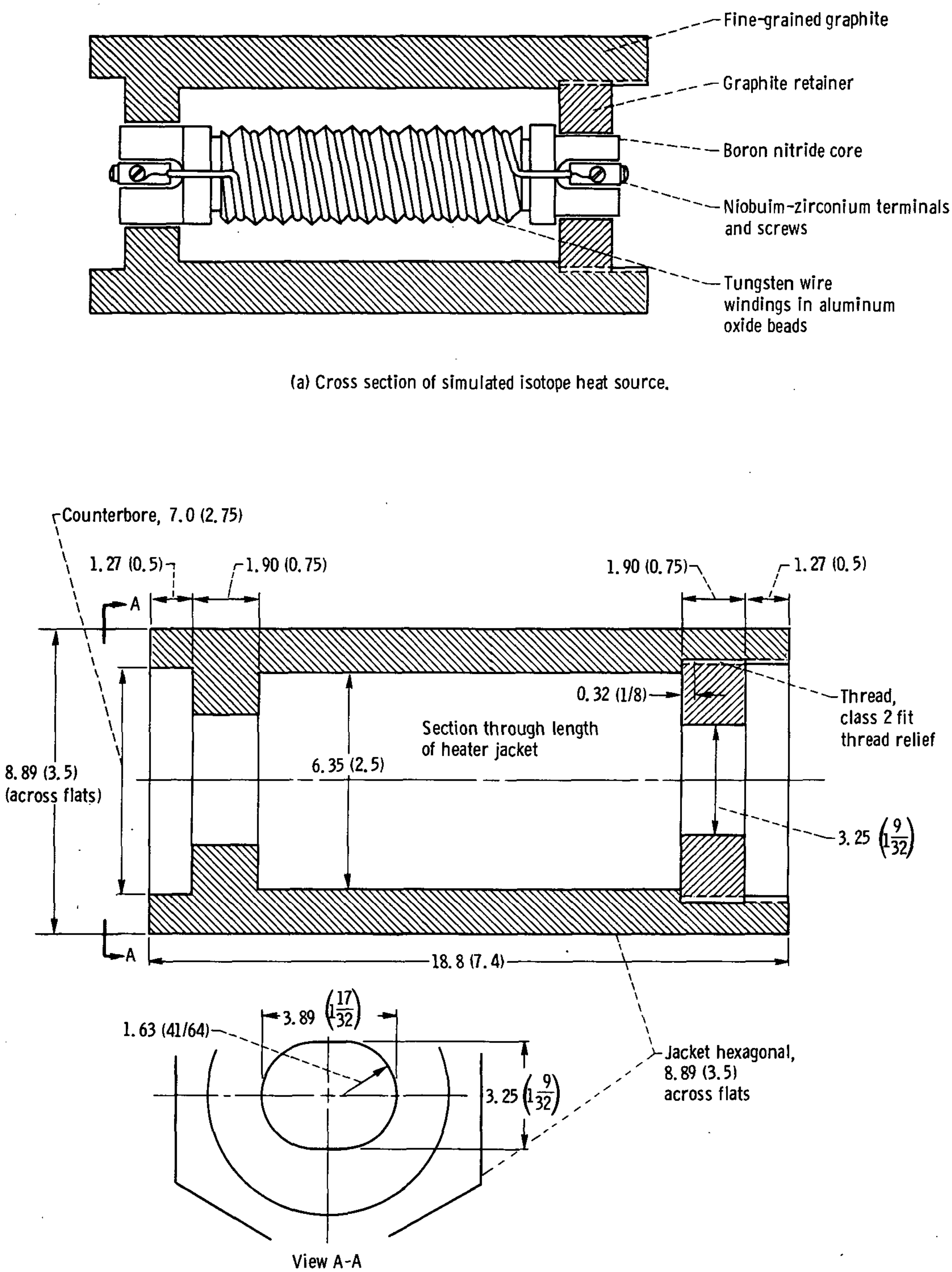


Figure 3. - Isotope heat source simulator.



(a) Cross section of simulated isotope heat source.

(b) Details of graphite enclosure. All dimensions are in centimeters (in.).

Figure 4. - Isotope heat source simulator.

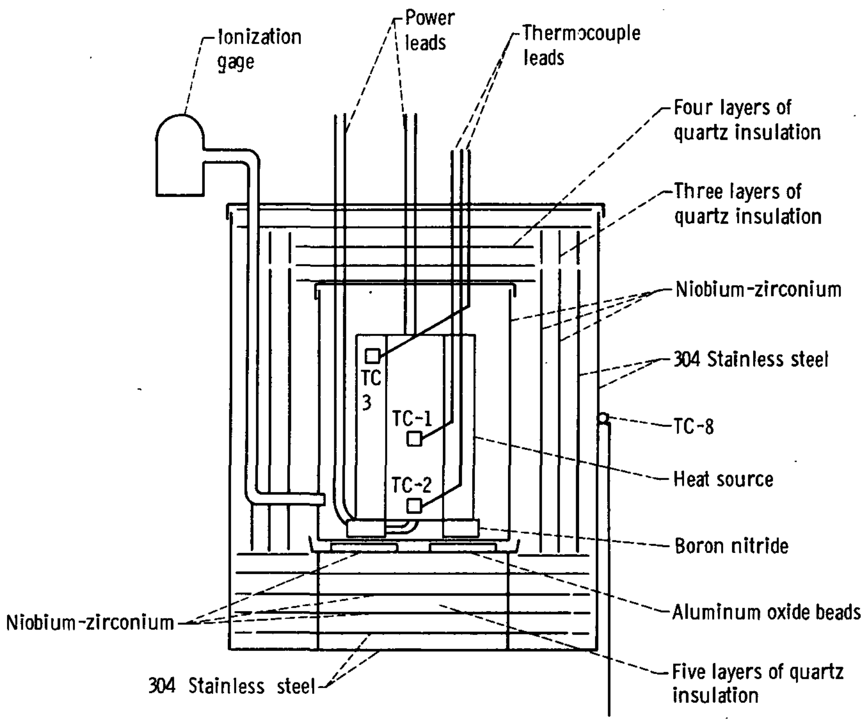


Figure 5. - Cross section of insulated container with heat source installed.

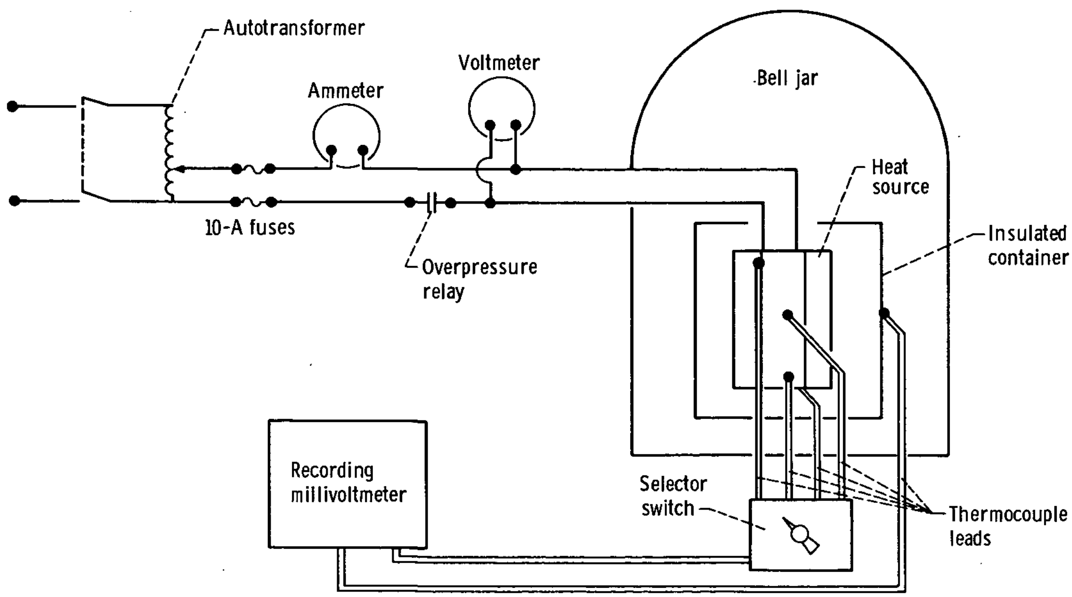


Figure 6. - Schematic diagram of test setup.

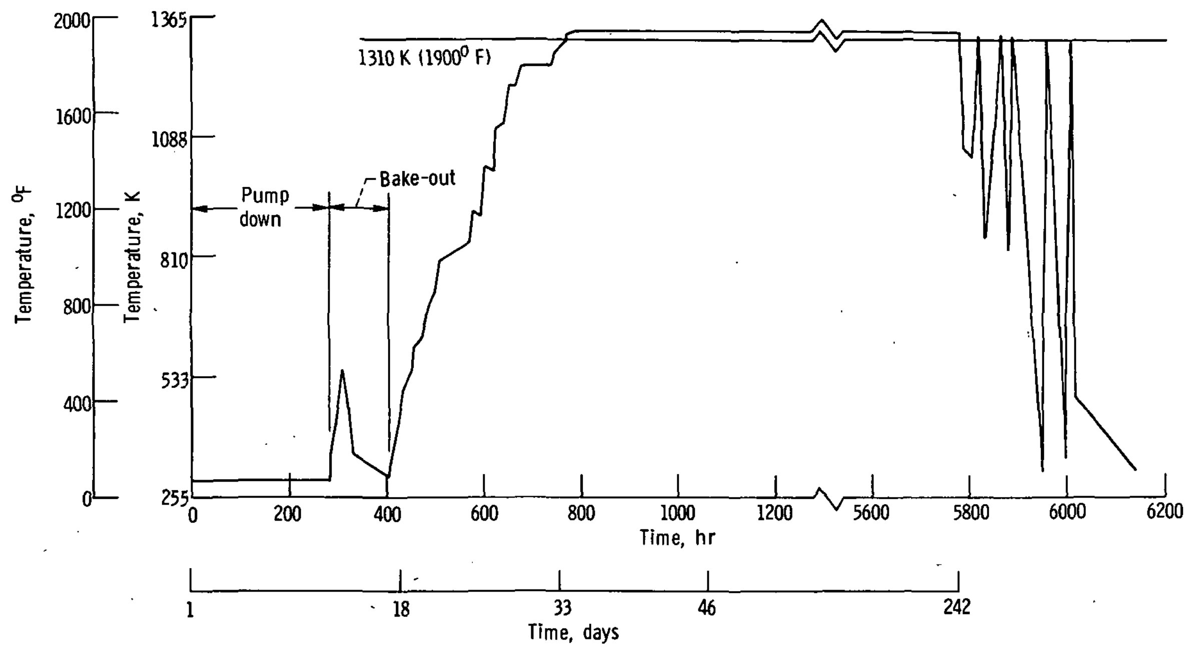


Figure 7. - Time-temperature history of isotope heat-source simulator test.

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